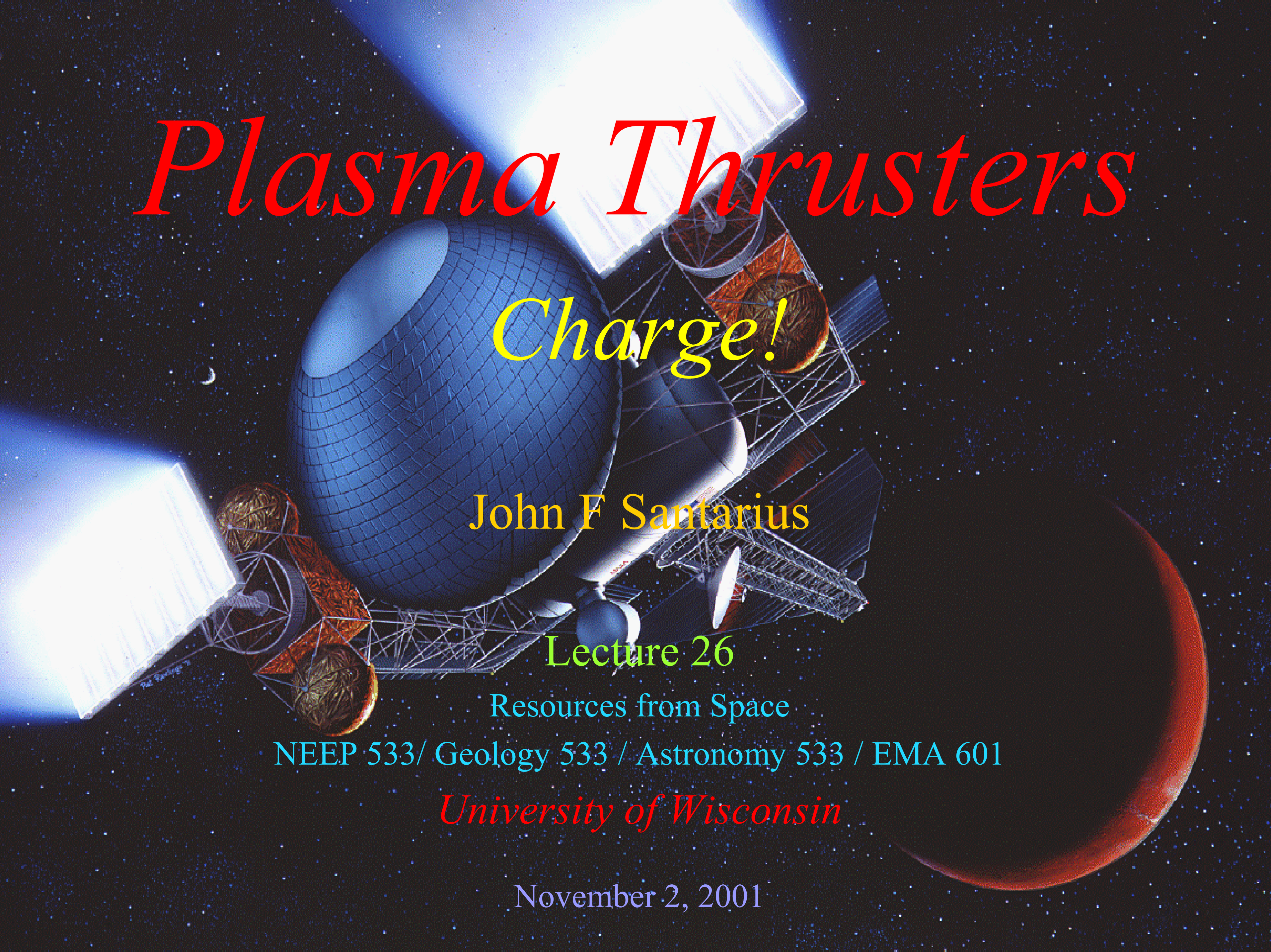


# *Plasma Thrusters*

## *Charge!*


John F Santarius


Lecture 26

Resources from Space

NEEP 533/ Geology 533 / Astronomy 533 / EMA 601


*University of Wisconsin*


November 2, 2001

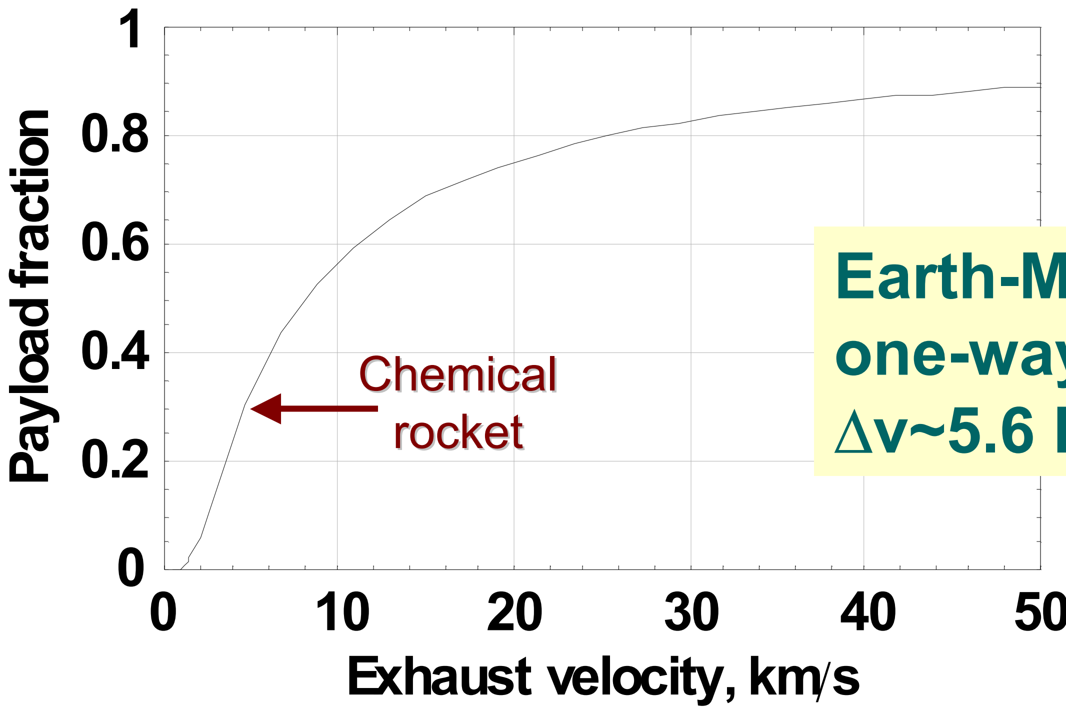
# Outline

- Low-thrust trajectories
- Plasma thrusters

# High Exhaust Velocity Gives Large Payloads

- This plot of the rocket equation shows why high exhaust velocity historically drives rocket design: payload fractions depend strongly upon the exhaust velocity.

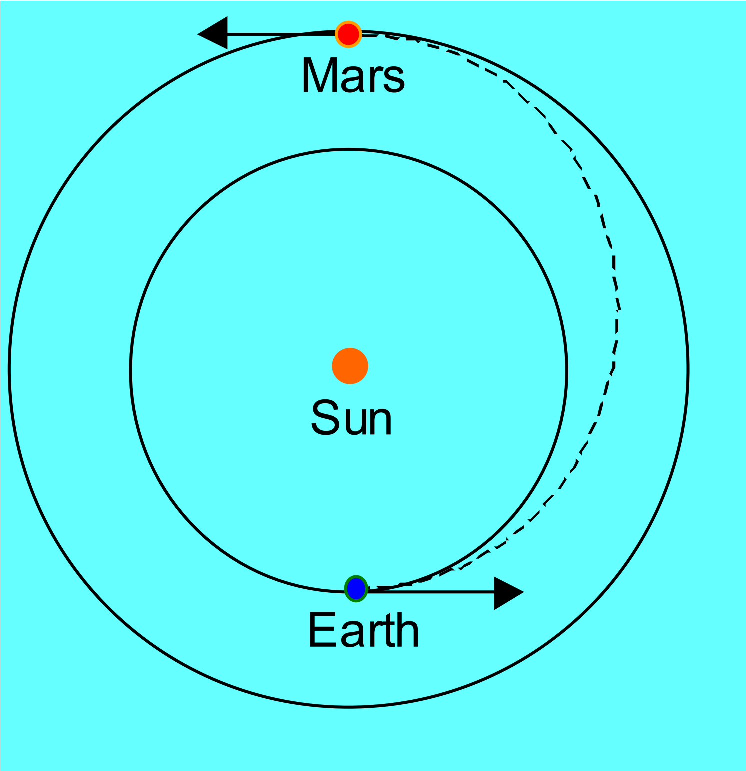
$$\frac{M_f}{M_i} = \exp\left(\frac{-\Delta v}{v_{ex}}\right)$$



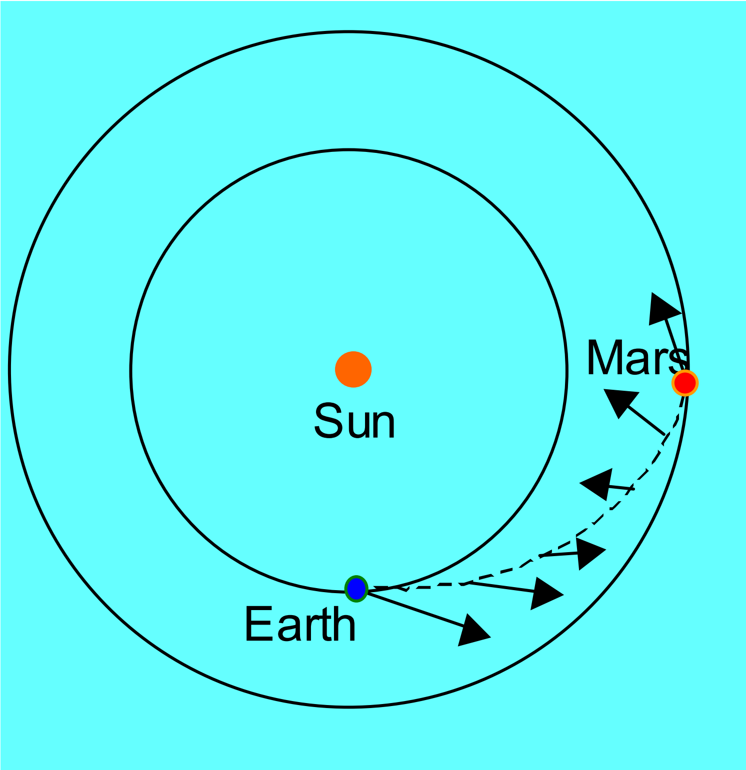

**Earth-Mars one-way trip: $\Delta v$~5.6 km/s**

# Taking Full Advantage of High Exhaust Velocity Requires Optimizing Trajectories

Chemical rocket trajectory (minimum energy)




Fusion rocket trajectory (variable acceleration)




Note: Trajectories are schematic, not calculated.

# Useful Propulsion Definitions

$M_w \equiv$ power and propulsion system mass

$M_l \equiv$ payload mass

$M_p \equiv$ propellant mass

$M_0 \equiv$ total mass = $M_w + M_l + M_p$

$\tau \equiv$ mission power-on time

$\dot{M} \equiv$ propellant flow rate = $M_p / \tau$

$F \equiv$ thrust = $\dot{M}\, v_{ex}$

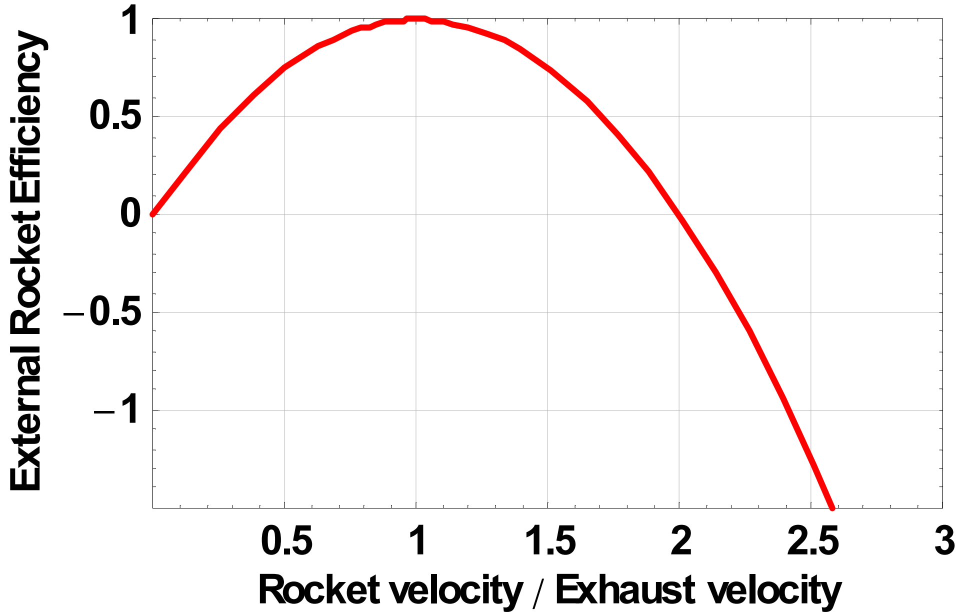
$P_w \equiv$ thrust power = $\frac{1}{2}\, \dot{M}\, v_{ex}^{\;2}$

$\alpha$ [kW/kg] $\equiv$ specific power = $P_w / M_w$

$v_{ch} \equiv$ characteristic velocity = $(2\alpha\tau)^{1/2}$

# Defining Separately Powered Rocket Efficiency Can Be Tricky

- For example: *External Rocket Efficiency*
  ≡ increment in rocket kinetic energy divided by kinetic energy change generated by rocket engine.




- *Negative efficiency!* At some point, exhausted propellant carries more kinetic energy than it had as part of the rocket.

# How Do Separately Powered Systems Differ from Chemical Rockets?

- Propellant not the power source.
- High exhaust velocity ($\gtrsim 10^5$ m/s).
- Low thrust ($\lesssim 10^{-2}$ m/s} $\equiv 10^{-3}$ Earth gravity) in most cases.
- Thrusters typically operate for a large fraction of the mission duration.
- High-exhaust-velocity trajectories *differ fundamentally* from chemical-rocket trajectories.

$$\frac{M_l + M_w}{M_l + M_w + M_p} = \exp\left(\frac{-\Delta v}{v_{ex}}\right)$$

$M_l$=payload mass

$M_w$=power and propulsion system mass

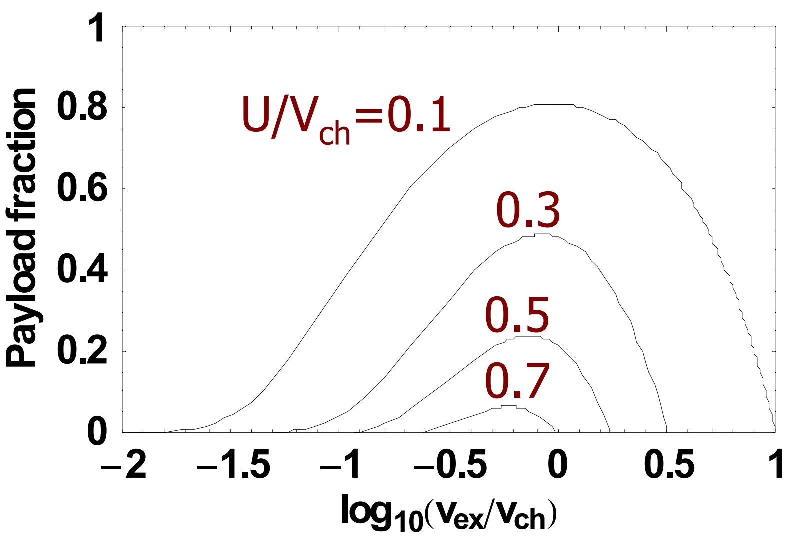
$M_p$=propellant mass

# Rocket Equation for Separately Powered Systems

- Explicitly including the power-plant mass using $v_{ch}$, the *characteristic velocity*, modifies the rocket equation:

$$\frac{M_l + M_w}{M_l + M_w + M_p} = \exp\left(\frac{-\Delta v}{v_{ex}}\right) \Rightarrow$$

$$\frac{M_l}{M_0} = \exp\left(\frac{-u}{v_{ex}}\right) - \frac{v_{ex}^2}{v_{ch}^2}\left[1 - \exp\left(\frac{-u}{v_{ex}}\right)\right]$$




$M_l$=payload mass

$M_w$=power and propulsion system mass

$M_p$=propellant mass

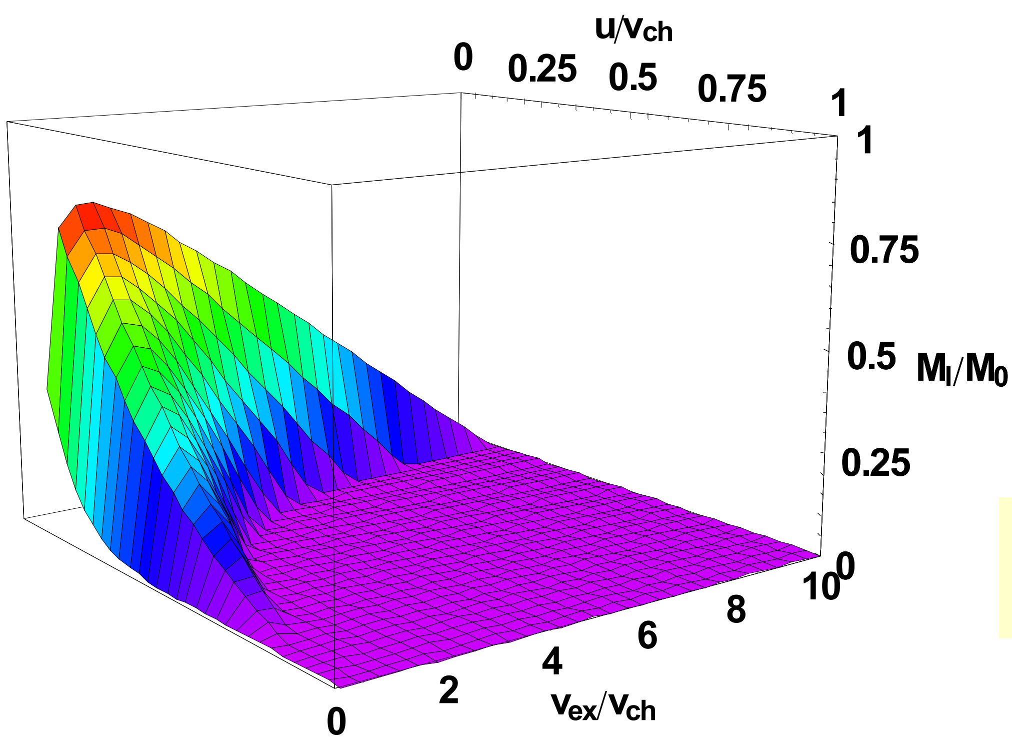
u ≡ mission energy requirement

$v_{ch}$ ≡ characteristic velocity = $(2\alpha\tau)^{1/2}$

$v_{ex}$ ≡ exhaust velocity

# Rocket Equation for Separately Powered Systems

$$\frac{M_l}{M_0} = \exp\left(\frac{-u}{v_{ex}}\right) - \frac{v_{ex}^2}{v_{ch}^2}\left[1 - \exp\left(\frac{-u}{v_{ex}}\right)\right]$$




u ≡ mission energy requirement

$v_{ch}$ ≡ characteristic velocity $= (2\alpha\tau)^{1/2}$

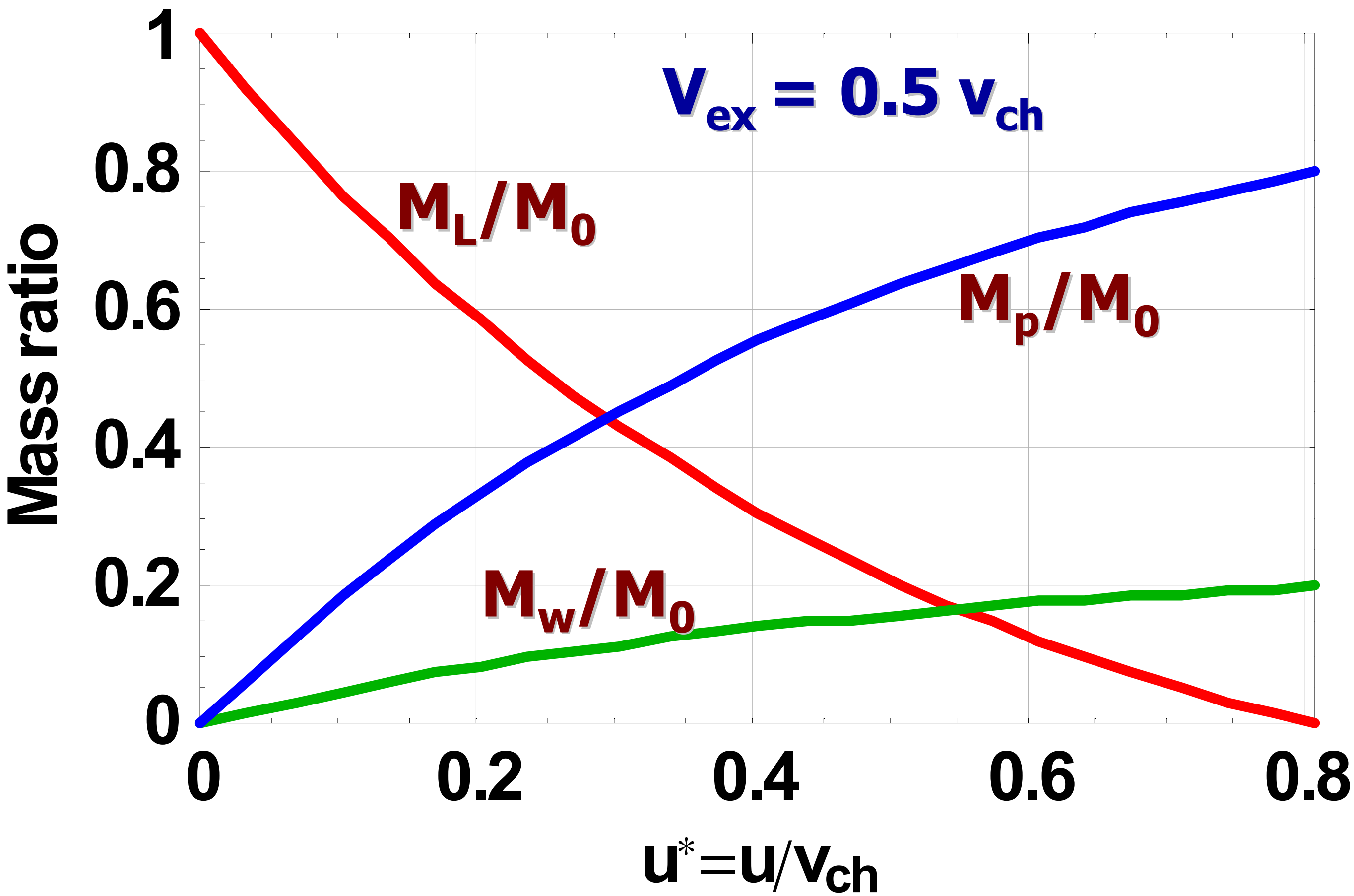
# Mass Ratios Vary Simply with $u/v_{ch}$ and $v_{ex}/v_{ch}$

$M_w \equiv$ power plant mass

$M_p \equiv$ propellant mass

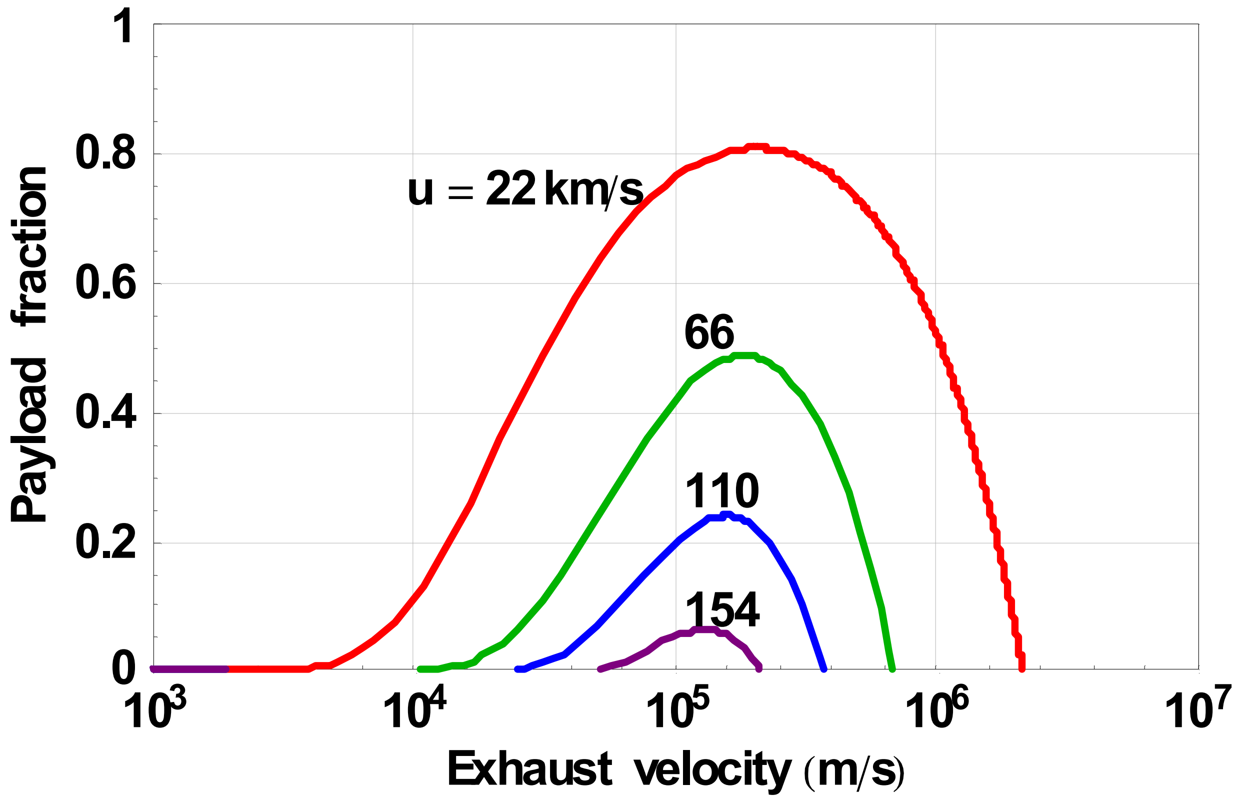
$M_L \equiv$ payload mass

$M_0 \equiv$ total mass



# Earth-Mars Mission Characteristic Velocity Example: α=1 kW/kg; τ=9 months (one-way)

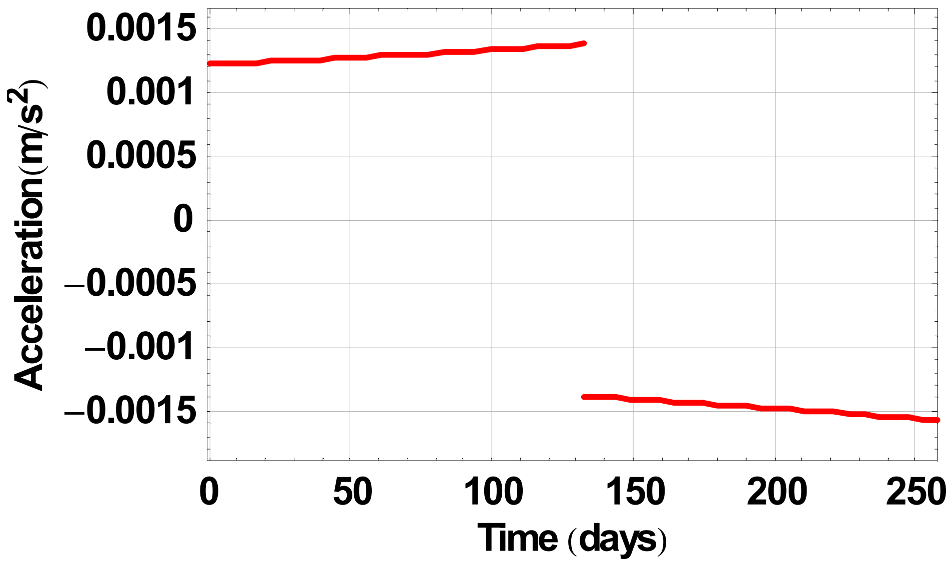
- Characteristic velocity ≡ $v_{ch} \equiv \sqrt{2\alpha\tau}$ = 220 km/s
  - Note: remember to use *W/kg not kW/kg* for α when calculating $v_{ch}$!
- $v_{ch} \approx$ 40 times Hohmann Δv (5.6 km/s for Earth-Mars missions)



# Earth-Mars Mission Characteristic Velocity Example: $\alpha$=1 kW/kg; $\tau$=9 months (one-way)

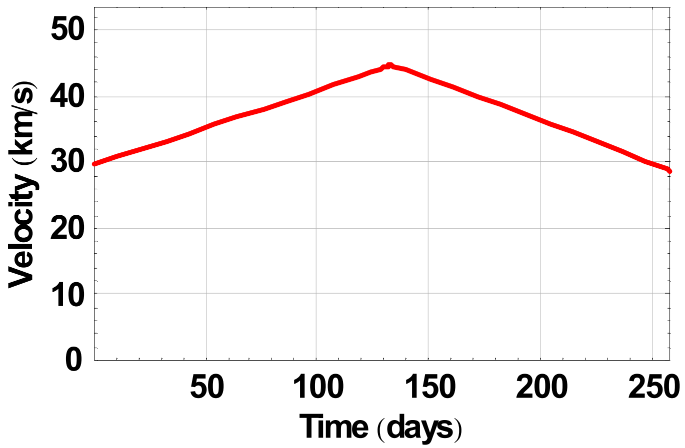
- Guidance from the plot on the previous viewgraph plus an educated guess for the turnaround terminal velocity allows self-consistent (that is, meeting boundary conditions) solutions for low-thrust trajectories to be found.

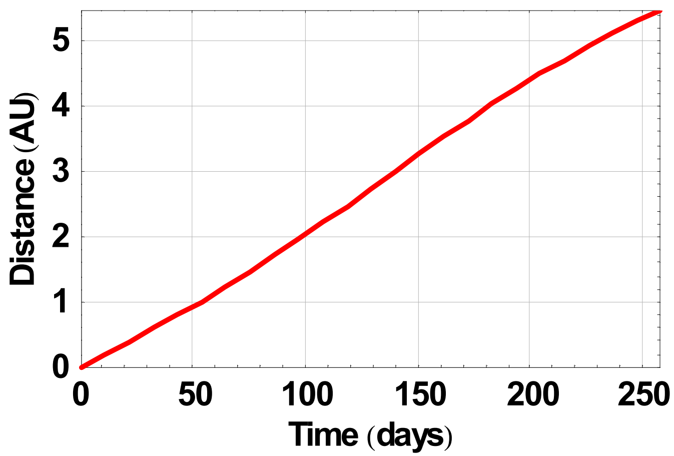
- For example, choosing a turnaround velocity of $v_{Earth}+0.26\ v_{ch}$ leads to the acceleration program shown.

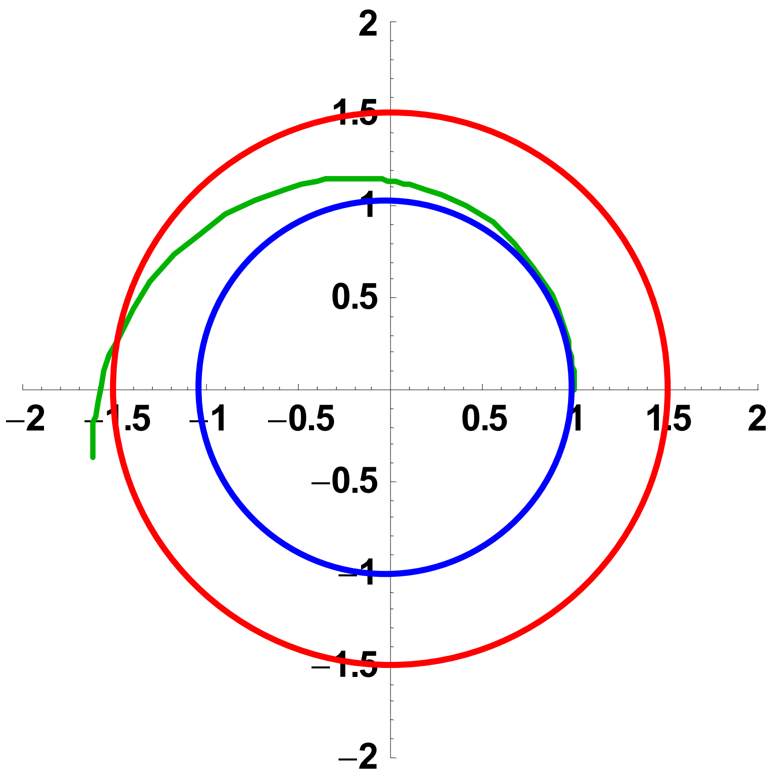


# Earth-Mars Mission Example

- The corresponding velocity and distance values are shown, as is the approximate trajectory.



# Earth-Mars Mission Example Summary Parameters

| *Parameter* | *Low-Thrust* | *Chemical* |
|---|---|---|
| One-way travel time | 258 days | 258 days |
| Specific power | 1 kW/kg | ∞ |
| Characteristic velocity | 150 km/s | -- |
| Exhaust velocity | 119 km/s | 4.5 km/s |
| Total velocity increment | 24 km/s | 5.6 km/s |
| Distance traveled | 5.5 AU | 5.5 AU |
| Propellant flow rate | ~1.5 g/s | ? |
| Thrust force | 0.17 kN | ? |
| Initial thrust-to-weight | 0.00012 | ? |
| Payload ratio | 0.7 | 0.29 |

# Earth-Mars Mission Example
# Summary of Masses

| | *Low-Thrust* | *Chemical* |
|---|---|---|
| Payload | 100 Mg† | 100 Mg† |
| Power and propulsion | 10 Mg | 0 Mg |
| Propellant (acceleration phase) | 17 Mg | -- |
| Propellant (deceleration phase) | 16 Mg | -- |
| Propellant total | 33 Mg | 244 Mg |
| Total initial mass | 143 Mg | 344 Mg |

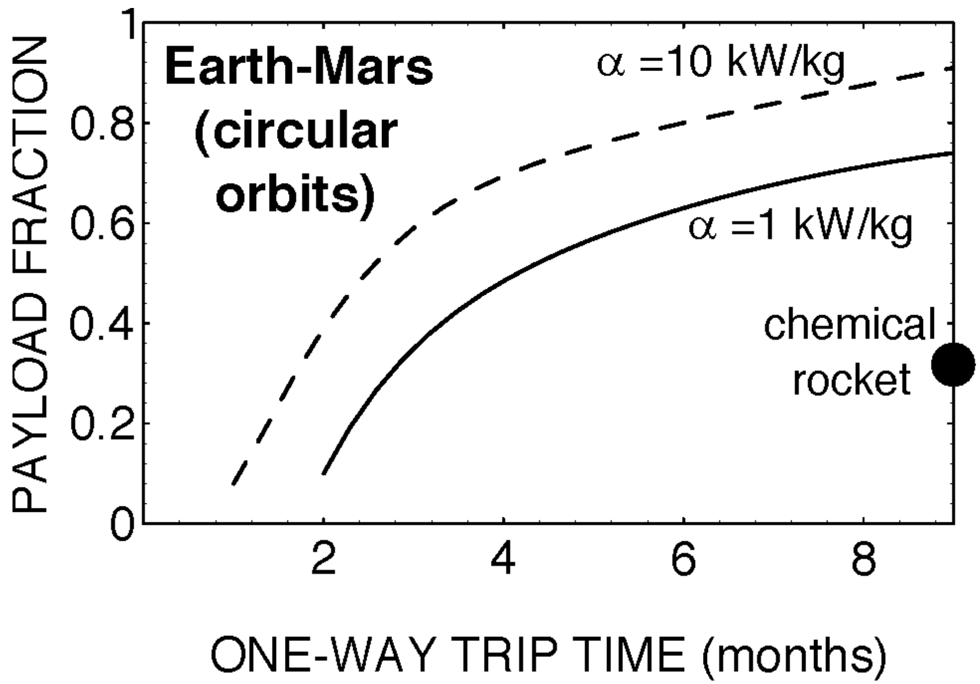
† Note: 1 Mg ≡ 1 tonne

# Efficient Solar-System Travel Requires High-Exhaust-Velocity Propulsion

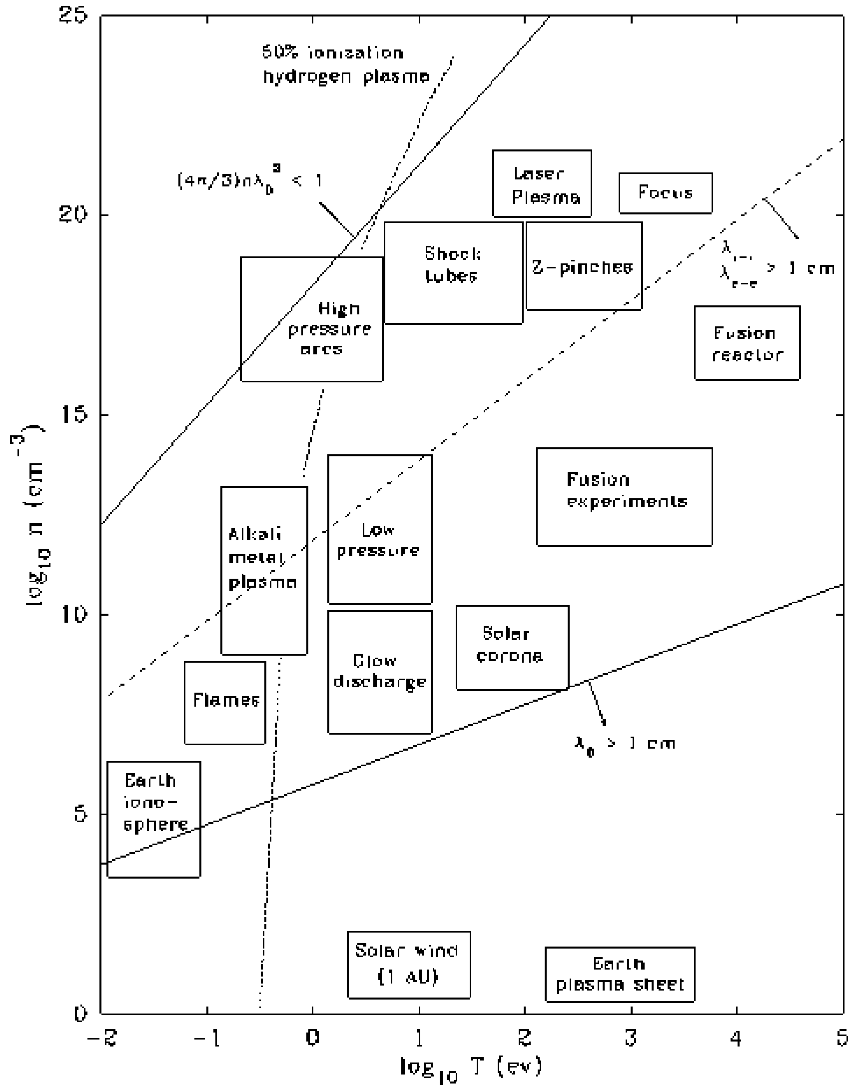
- Electric power can be used to drive high-exhaust-velocity plasma or ion thrusters, or fusion plasmas can be directly exhausted.
- Allows fast trip times or large payload fractions for long-range missions.
- Uses relatively small amounts of propellant, reducing total mass.

**Fusion rocket**

**($\alpha \equiv$ *specific power*)**



# Plasmas (Hot, Ionized Gases) Exist in Many Different Regimes



# Governing Principles for Analyzing Plasma Thrusters

- Maxwell's equations

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

- Force equation

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B} - \nabla P$$

- Atomic physics
- Plasma-surface interactions
- Sheath physics
- Statistical mechanics
- Magnetohydrodynamics

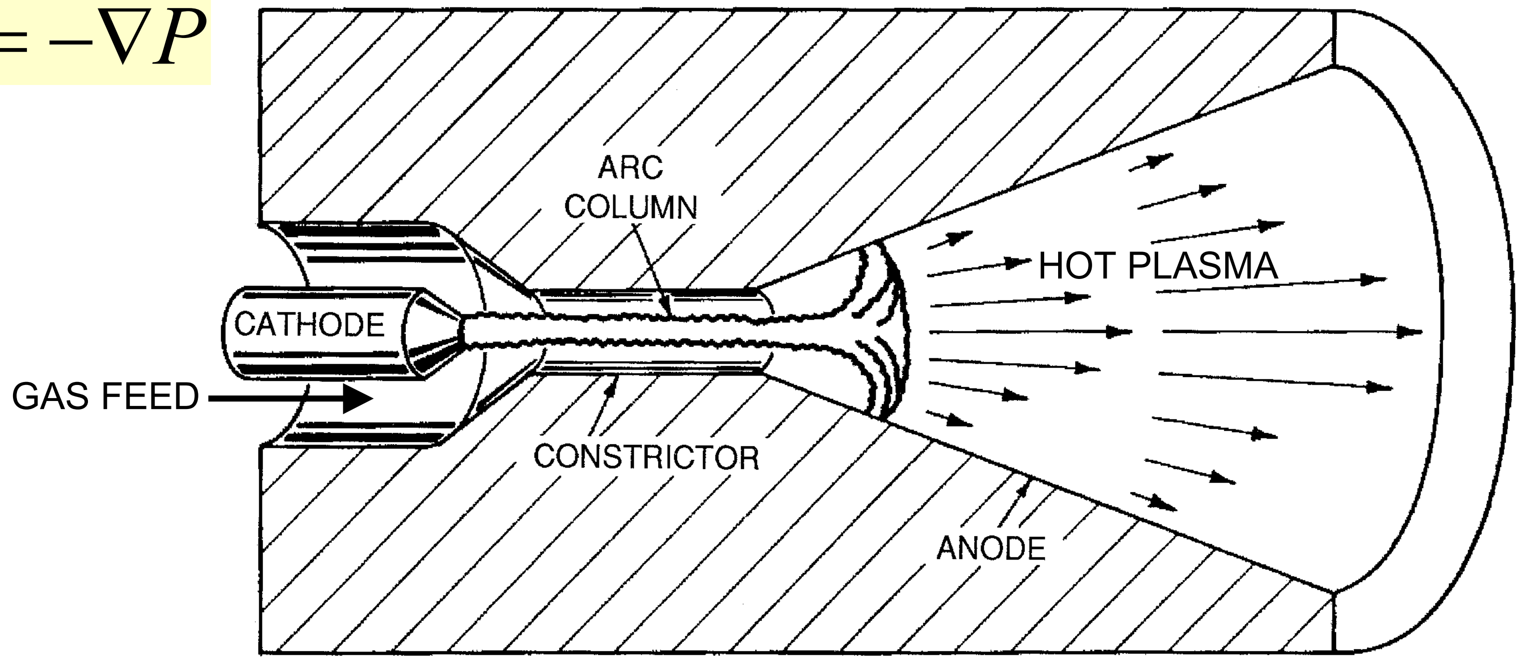
# Plasma (Electric) Thrusters Come in Three Basic Varieties

- Electrothermal
  - Plasma pressure driven
  - Modest thrust, relatively low exhaust velocity
- Electrostatic
  - Voltage-gradient driven
  - Low thrust, high exhaust velocity
- Electrodynamics
  - Complicated electromagnetic driving forces
  - Modest thrust, modest exhaust velocity

# Electrothermal Thruster

- Basic principle of electrothermal thrusters is to create a hot plasma that expands because of internal pressure.

$$\vec{F} = -\nabla P$$

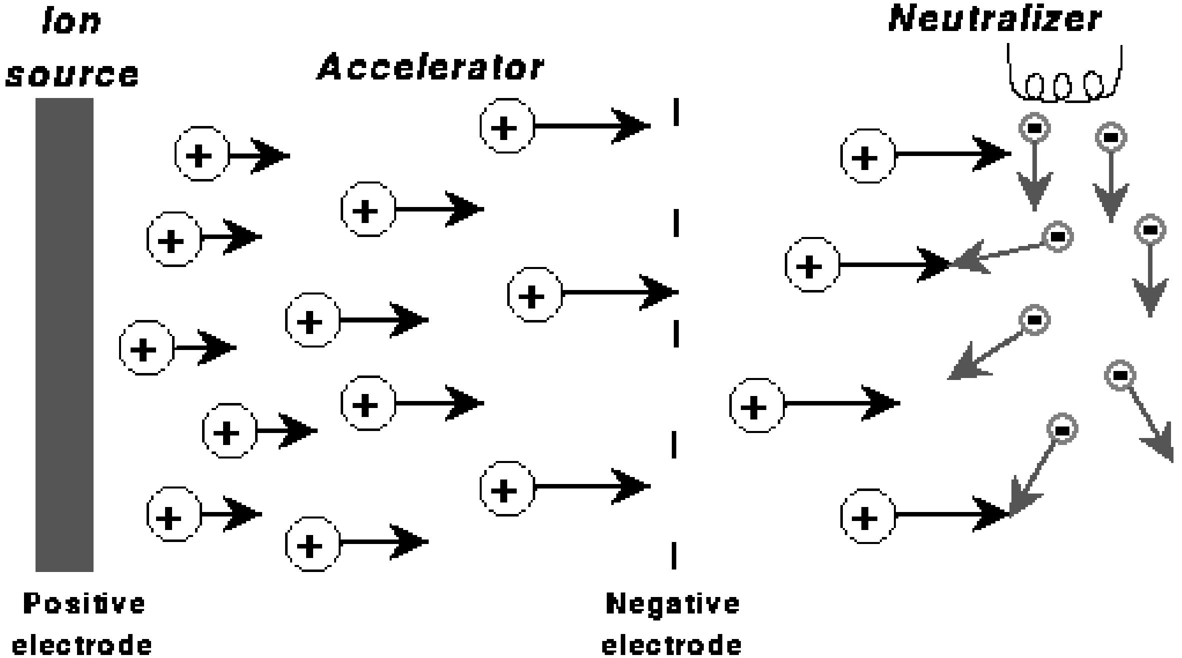



From Robert Jahn, Physics of Electric Propulsion (1968)

# Electrostatic Thruster

- Basic principle of electrostatic thrusters is to cause ions to pick up energy by falling down a potential hill.

$$\vec{F} = q\vec{E} = -q\nabla\Phi$$

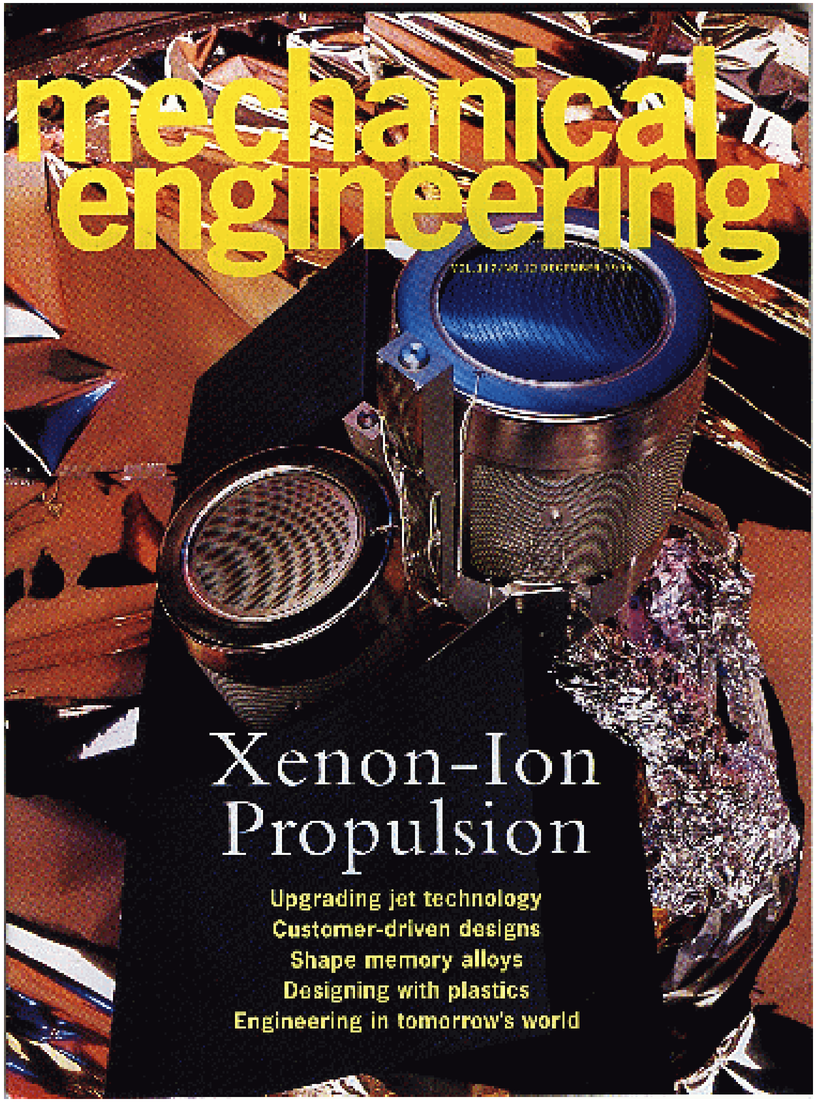



$$\Phi = V_+$$

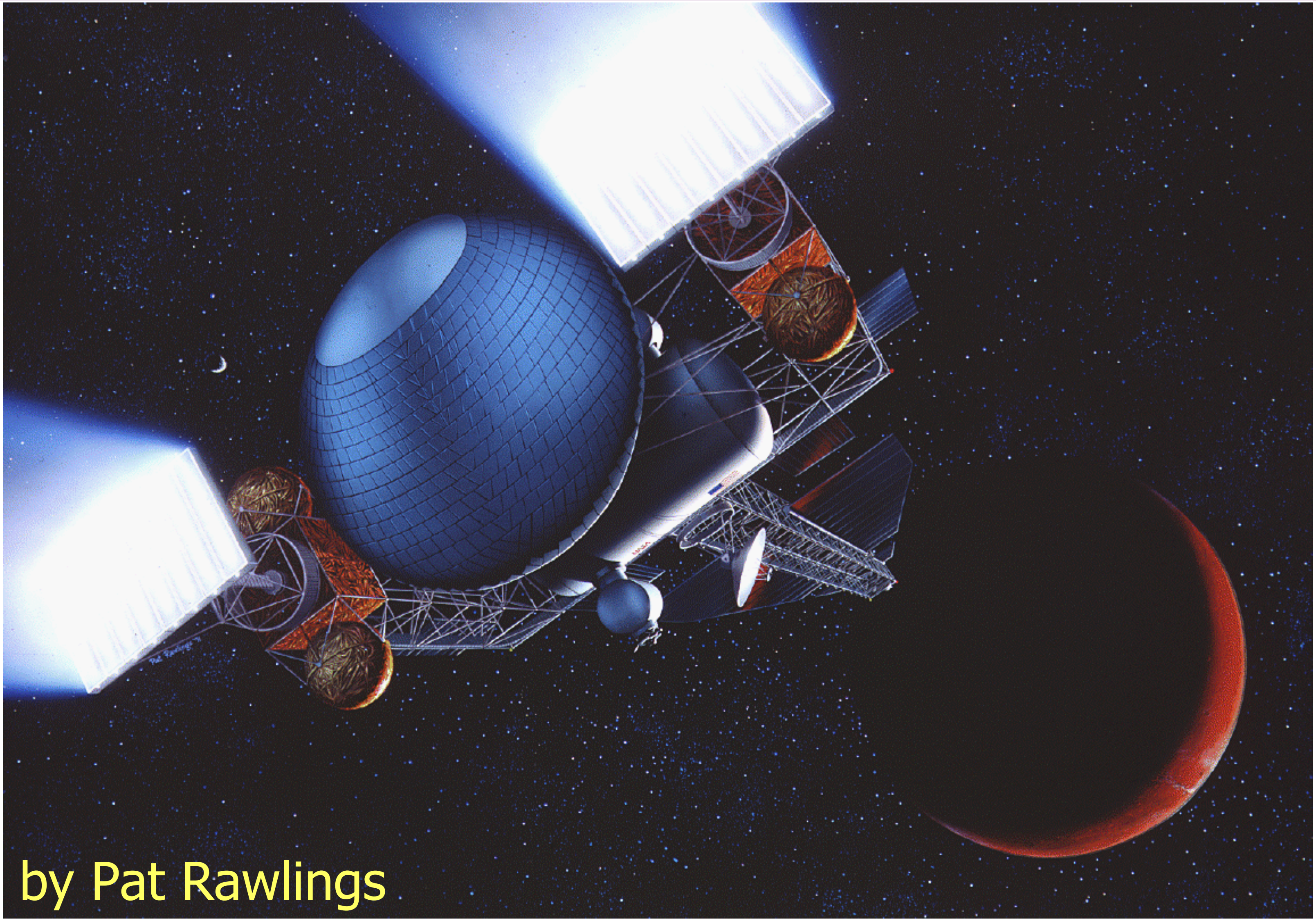
$$\Phi = V_-$$

# Electrostatic Thruster Hardware Example

- The xenon-ion thruster shown at right was launched in 1998 on the Deep Space I spacecraft.
- After initial shakeout problems, it substantially exceeded its design lifetime.



# Nuclear-Electric Propulsion (NEP) Conceptual Design Using Ion Thrusters



# Electromagnetic Thrusters

- Electromagnetic thrusters depend on both electric and magnetic fields for their operation.
  - Can be steady-state or pulsed.
  - The presently most important varieties appear below.

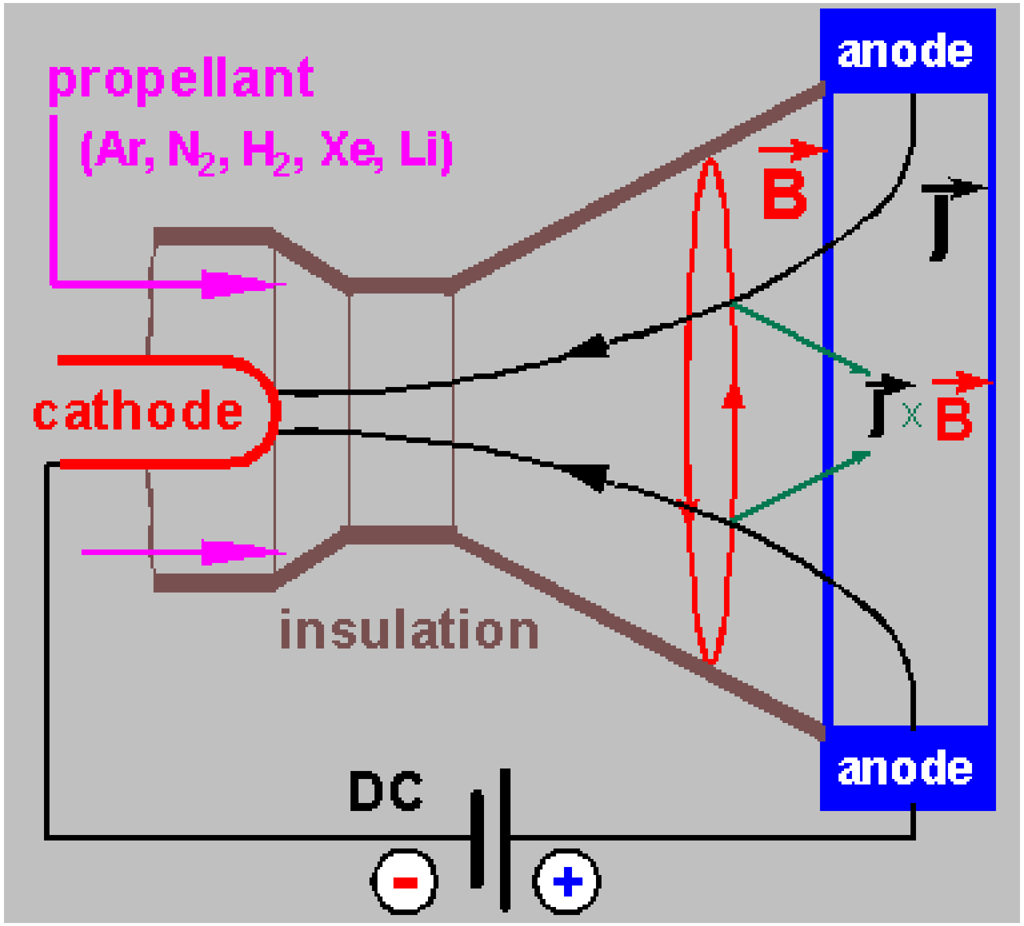
| ***Thruster Type*** | ***Key Operating Principle*** |
|---|---|
| MPD | J x B force on plasma |
| SPT (button) | Hall effect (E x B drift) |
| Pulsed-plasma | J x B force moving current |
| Pulsed-inductive | Radio-frequency wave induced current |

# Magnetoplasmadynamic (MPD) or Lithium Lorentz Force Thruster

- Basic principle of MPD thrusters is to utilize the force perpendicular to a current crossing a magnetic field.

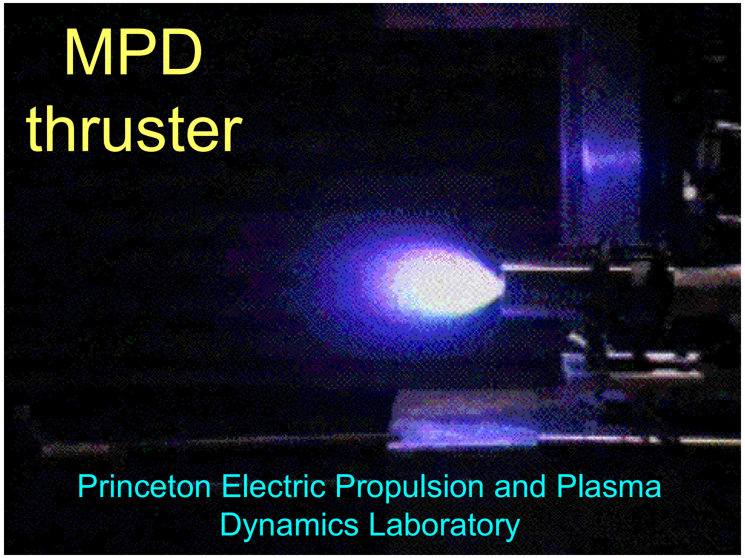
$$\vec{F} = \vec{j} \times \vec{B}$$

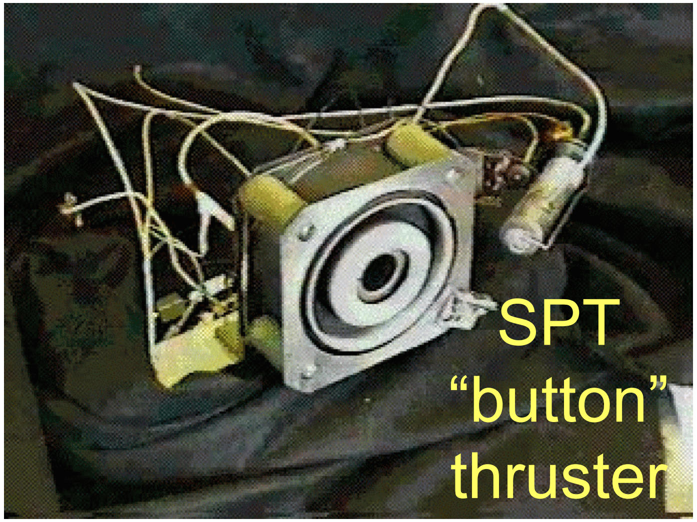
$$\vec{j} = nq\vec{v}$$



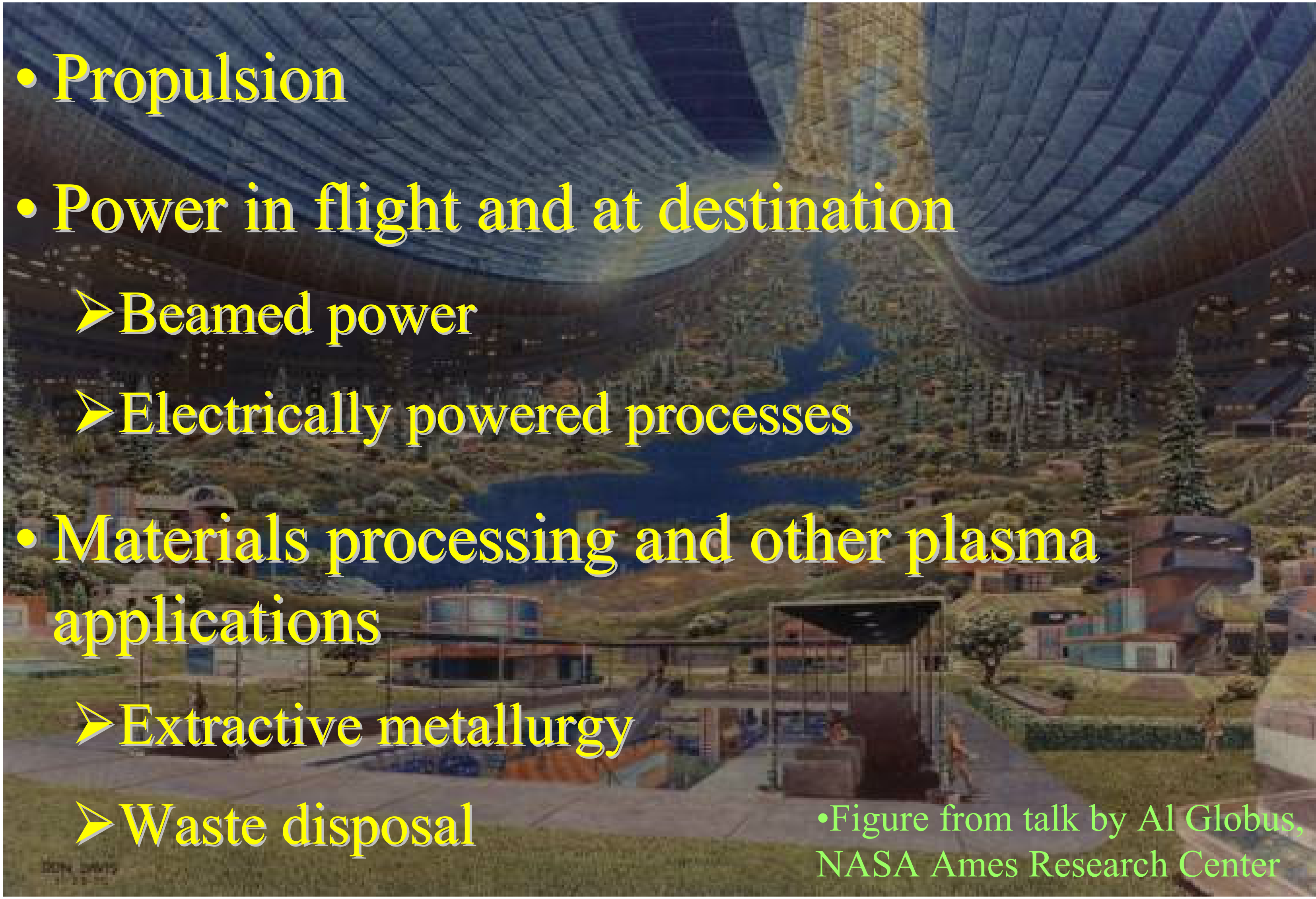

From University of Stuttgart's web page:
www.irs.uni-stuttgart.de/RESEARCH/EL_PROP/e_el_prop.html

# Electrodynamic Thruster Hardware Examples




# Carrying a Separate Power Source Gives Flexibility



- Propulsion
- Power in flight and at destination
  - Beamed power
  - Electrically powered processes
- Materials processing and other plasma applications
  - Extractive metallurgy
  - Waste disposal

•Figure from talk by Al Globus, NASA Ames Research Center

# Low-Thrust Trajectory Analysis References


- Ernst Stuhlinger, *Ion Propulsion for Space Flight* (McGraw-Hill, New York, 1964).
- Krafft A. Ehricke, *Space Flight: II. Dynamics* (Van Nostrand, Princeton, 1962).
- Howard S. Seifert, ed., *Space Technology* (Wiley, New York, 1959).
- http://fti.neep.wisc.edu/~jfs/neep533.lecture9.trajectories.99.html